

The Classic Barrovian Metamorphic Sequence of Dutchess County and Its Structural and Stratigraphic Context in the Taconic Orogeny

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Introduction

Metamorphism in Dutchess County, NY has been considered a classic example of Barrovian-type metamorphism since early mapping of the region (Knopf, 1927; Balk, 1936; Barth, 1936). Interestingly enough, few workers have extended the work that Balk and Barth began. People have been willing to accept it as classic without further testing (notable exceptions are the work of Bence, Vidale, Whitney and their coworkers). In his 1998 NYSGA field guide to Dutchess County, Donnelly remarks that "The area remains one of the clearest Barrovian sequences in the world." And yet, there are many unanswered questions about the metamorphism. Some questions arise because of the complexities of the stratigraphy and the timing of episodes of deformation, metamorphism, and fluid flow. Others arise because of new analytical techniques that can be brought to bear to help elucidate the complex metamorphic history of the rocks.

The metamorphic sequence in Dutchess County begins with chlorite grade rocks at the Hudson River (Figure 1; Stop 1 in this guide; all pelitic rocks east of the Shawangunk Ridge in Ulster County contain chlorite, although whether detrital or authigenic/metamorphic is not always clear) and progresses beyond the second sillimanite (sillimanite-orthoclase) isograd near the Connecticut border (Stop 8). Rocks now exposed over a distance of about 30 km were tectonically buried as much as 25 km (Bence and McLelland, 1976; Whitney et al., 1996b) during the Taconic Orogeny. The sequence was subsequently tilted to its present orientation during uplift to the east associated with the Acadian Orogeny. In addition to isograd mineral growth, the prograde sequence also demonstrates fabric development from phacoidal cleavage at the Hudson River, through phyllites and schists in the middle of the county, to gneissic fabric near the Connecticut border.

Balk (1936) and Barth (1936) believed that metamorphism in Dutchess County was due to "steeping" of the pelitic rocks in igneous fluids emanating from magmas deeper within the crust. They cited as evidence the fact that granitoid intrusions are found to the east and south (in Connecticut and Westchester County, NY, respectively), on strike with the increasing metamorphic gradient mapped in the county. Some of these granites, however, contain muscovite suggesting that they are peraluminous S-type granitoids formed by partial melting of a source dominated by sedimentary material (Winter, 2001, p. 350). Some outcrops in the sillimanite zone of Dutchess County contain Qtz-fsp-mica veins which Barth (1936) interpreted as apophyses from the granitoid intrusions. These veins have also been interpreted as leucosomes from anatexis of the sediments (Bence and McLelland, 1976; Whitney, personal communication, 2009). Most workers now believe that the heat for metamorphism was generated by tectonic burial of the rocks during the Taconic Orogeny although fluid flow was probably an important heat-transfer mechanism (Whitney et al., 1996b).

The classic nature of the metamorphic sequence in Dutchess County, and its excellence for teaching, mean that a number of very good field guides are available for the area (Bence and McLelland, 1976; Donnelly, 1998; Whitney and Peck, 2004). Bence and McLelland's 1976 NYSGA field guide provided a thorough discussion of the sequence, and identified many of the outcrops that have since become almost mandatory on local field trips (Stops 2, 4, 6, 7 and 9 in this guide). They also included whole rock chemical analyses, and microprobe analyses of individual minerals that are very helpful for understanding metamorphic conditions. Additional sources of whole rock analyses are Vidale (1974b), Whitney et al. (1996b) and Donnelly (1998). Whitney et al. (1996b) also published microprobe analyses of individual mineral grains.

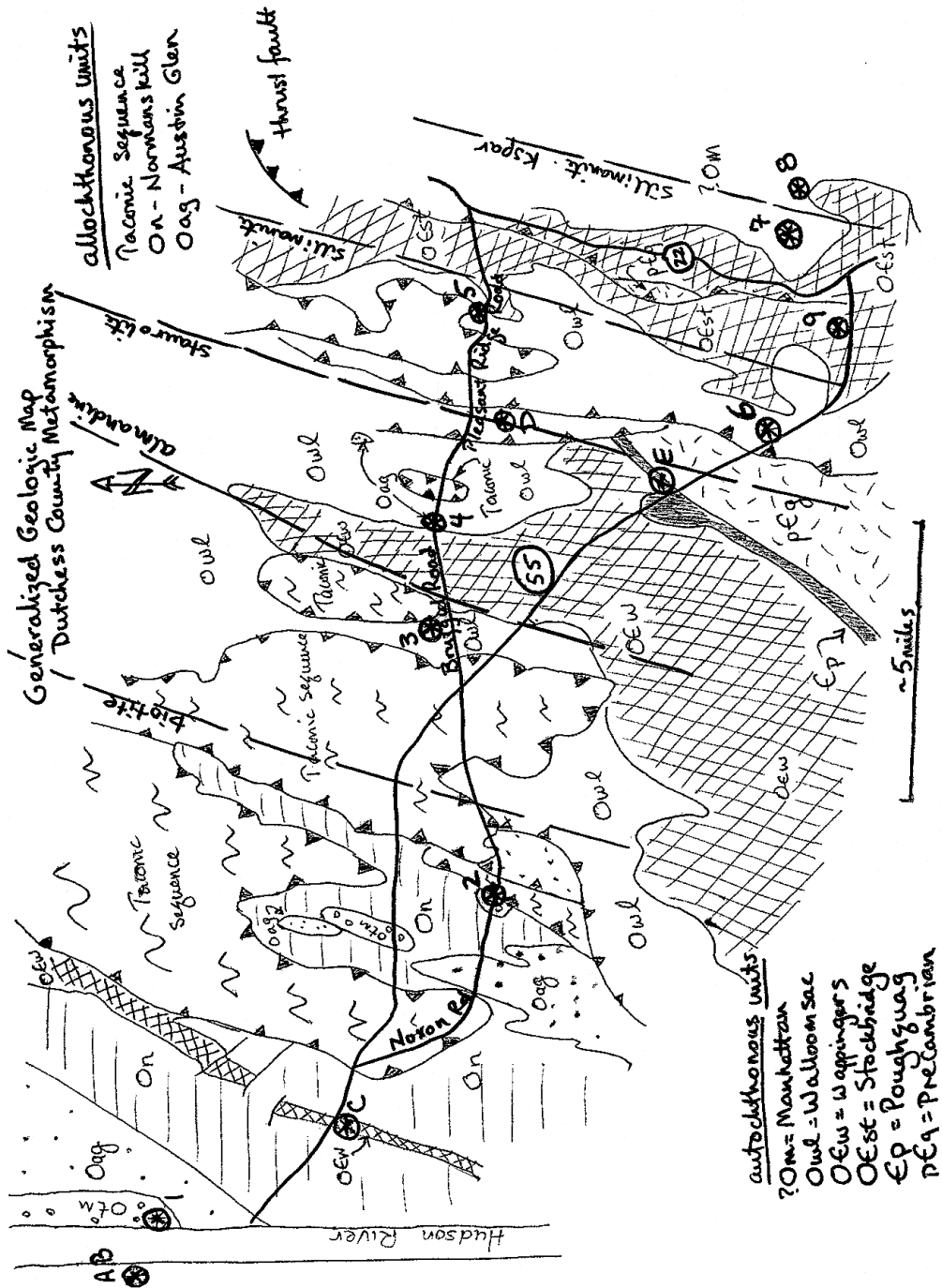


Figure 1. Generalized geologic map of Dutchess County showing main stratigraphic and structural features, metamorphic iso-grads, and stop location. (after Fisher et al., 1970).

This field trip will follow Bence and McLelland (1976) and Whitney and Peck (2004) for the higher grade (chlorite grade and higher) outcrops. To this, we add several additional topics:

- We will make stops in the lower part of the chlorite zone at which we discuss the evidence for low grade metamorphism and the difficulties in distinguishing metamorphic from detrital chlorite
- We stop at exposures of the Taconic melange and discuss its significance.
- We comment on some recent proposals relevant to the sometimes confusing stratigraphic nomenclature.
- We comment on the development of metamorphic fabrics across the county.
- We provide photomicrographs for discussion of relationships that are difficult to examine in outcrop.
- We include additional equations and AFM projections to illustrate possible reactions.

Stratigraphic Nomenclature

We do not propose revisions to the stratigraphy of Dutchess County, but note that some terms are the subject of confusion which has been discussed in the literature. In particular the terms “Snake Hill Shale”, and “Normanskill” Formation or Group cause confusion, in part because of the stratal disruption of these units along the Taconic front, but also because formational names have been applied to both biostratigraphic and lithostratigraphic units. Similarly, usage of the term “Taconic melange” requires clarification.

Dark shales and slates associated with the Taconic front and further west are sometimes referred to as "Snake Hill Shale" (e.g., Fisher and Warthin, 1976; Fisher, 1977). In Dutchess County shales in this stratigraphic position are also mapped as the Normanskill Formation (On), although Rickard and Fisher (1973) argued, and most investigators now agree, that that Normanskill Formation is entirely allochthonous. The term "Snake Hill Shale" is also sometimes used to refer to the matrix of the Taconic melange (Otm) and has been used to refer to exposures of Taconic melange matrix in the Poughkeepsie area (e.g., outcrops in the Arlington and Spackenkill neighborhoods of the Town of Poughkeepsie near Vassar College). Kidd et al. (1995) and English et al. (2006) discourage this broad usage of the term "Snake Hill Shale" (also pers. comm. G. Baird, 2009). We accept this restricted usage, which regards the Snake Hill as coherent stratigraphic blocks of lithologies similar to the "type" example bordering Saratoga Lake. These rocks have been caught up in Taconic thrusts, and are likely blocks with melange.

Similarly, the type locality of the “Normanskill” Formation (or Group) at Normanskill Gorge south of Albany is a block within the Taconic melange (Vollmer, 1981), where it comprises Austin Glen aspect graywacke and shale. However the term Normanskill Formation was extended from there to include Austin Glen (greywacke and shale), Mount Merino (black and green chert and siliceous argillites), and later the Indian River (red slate) as members (Ruedemann, 1942; Fisher, 1977), and later as formations when Normanskill was elevated to Group status (Fisher, 1977; see discussions in Vollmer, 1981; Cunningham, 1991; and Kidd et al., 1995). -We favor the proposal of Kidd et al. (1995) to abandon using the term “Normanskill” as a group or formation name, as it has strong biostratigraphic connotations and has been widely applied to very diverse lithologies.

The Austin Glen “type” locality is near Catskill, New York and it is widely exposed along the west side of the Hudson River (Vollmer, 1981; Marshak, 1990; Cunningham, 1991) including large exposures at the Mid-Hudson Bridge (Cunningham, 1991; Optional Stops A and B) directly west of Poughkeepsie. These rocks are highly deformed and are in most cases clearly tectonically transported (Vollmer, 1981; Cunningham, 1991). They are often associated with Mount Merino, but depositional contacts are not preserved. Generally, exposures of the Austin Glen and Mount Merino (many are on the west side of the Hudson River) are not considered part of the Taconic Allochthon as traditionally defined, because they lie west of Logan's (or Emmon's) line (e.g., Fisher, 1977), however structurally they are essentially lower thrust sheets (“slices”) (Bosworth and Vollmer, 1981).

To the west, deformation in Austin Glen and related flysch formations (e.g., Schenectady Formation) decreases, and they overlie the carbonate shelf sequence (Fisher, 1977). The term Pawlet has been used for Austin Glen equivalent rocks in the northern Taconics (Zen, 1961) where it has been shown to be conformable with the underlying Mount Merino, Indian River and Poultny Formations of the Taconic sequence (Rowley et al, 1979). The westerly prograd-

ation of the Austin Glen/Pawlet flysch over the slope/shelf sequence has been explained as due to the migration of a foreland basin as the Taconic Allochthon progressed westward over the continental margin and onto shelf sequence (Bird and Dewey, 1970; Rowley and Kidd, 1981). Note that “Austin Glen” has been used to include both flysch deposited on the continental shelf in front of, and subsequently overridden by, the Taconic Allochthon, and flysch deposited on the allochthonous Taconic continental rise sequence (i.e., Mount Merino and Indian River) and transported with it.

Within Dutchess County, metapelites mapped as conformable with the underlying Wappinger Group limestones are referred to as the Walloomsac Formation (Fisher, 1977), and are thus considered to be exposed structurally within windows beneath the Taconic Allochthon, or brought up as thrust slices along with the underlying shelf carbonate and Precambrian basement. The Walloomsac is thought to be correlative with flysch sequences deposited west of the allochthon, as well as the Manhattan schist (Fisher, 1977), mapped in eastern Dutchess County.

The Taconic melange is not a stratigraphic unit, but rather a complex tectonic unit consisting of centimeter to hundred meter scale blocks of various lithologies, dominated by graywacke, within a phacoidally cleaved scaly matrix. The blocks include stratally disrupted sequences (“broken formations”) as well as olistostromic components. The melange occurs in distinct zones, which may be meters to kilometers across, and which represent high strain zones associated with the emplacement of the Taconic Allochthon (Vollmer, 1981; Vollmer and Bosworth, 1984; Caine, 1991; Plesch, 1994; Kidd et al., 1995). Kidd et al. (1995) discuss other terms used for this unit, including “Poughkeepsie Melange” proposed by Fisher (Fisher & Warthin 1976, Fisher 1977), and propose the new name “Cohoos Melange” be used with the well-exposed sections along the Mohawk River as “type” sections (Plesch 1994). The Taconic melange is overlain by the Silurian-Devonian Helberburg Group along the Taconic unconformity south of Albany (Vollmer 1981; Kidd et al., 1995). Outcrops of melange matrix are widely exposed in the Poughkeepsie area. The typical irregular phacoidal cleavage (Stop 1) becomes more slaty in appearance to the east, and it becomes more difficult to discern small blocks and fragments within the melange.

Geologic History

The geologic history of the Dutchess County area, and of the whole Taconic belt that occupies much of eastern New York, is one of sedimentation, tectonic collision, and metamorphism. Ages of the various sedimentary rocks are constrained by graptolite zones, environments of deposition have been interpreted from textures, and provenances deduced by detrital clasts and geochemistry. The paleogeography, however, is less certain for it is very complex, and no one interpretation is unanimously accepted. In this field guide we follow the paleogeographic reconstructions of Rowley and Kidd (1981) shown in Figure 2.

In brief, the geologic history of Dutchess County is as follows (with formation names and abbreviations as shown on the Lower Hudson Sheet of the state geologic map (Fisher et al., 1970). Precambrian rifting of the Grenville-age supercontinent resulted in formation of a rifted margin sedimentary environment on the edge of the Iapetus Ocean (Figure 2A and B). Initial Paleozoic deposition in rift basins of the Grenville crust was the Poughquag Quartzite (Cpq). Carbonate platform deposition then ensued, forming the thick limestones and dolostones of the Wappinger Group (OCw, probably correlative with the Stockbridge Marble (OCst) in the eastern part of the county). During this same time interval, fine-grained clastic sediments of the Everett (Eev), Nassau (En), Germantown (Eg), Stuyvesant Falls (Osf), Mount Merino and Indian River (Omi) formations were deposited on the continental rise.

Eastward dipping subduction of the oceanic crust resulted in closing of the Iapetus Ocean basin. As the subduction zone approached ancestral North America (Figure 2C), the sediments on the continental slope and rise were incorporated into the accretionary wedge causing imbrication of the rise sediments by thrust faulting while flysch continued to be deposited in the migrating basin. Austin Glen/Pawlet (Oag) was deposited conformably on the Taconic continental rise sequence while Walloomsac (Owl) was deposited on shelf carbonates farther west.

Continued collision caused the obduction of the rise sediments onto the continental shelf carbonate and shale sediments, along with the already deposited Austin Glen/Pawlet flysch (Figure 2D). Austin Glen flysch continued to be deposited although the locus of deposition moved continuously west in advance of the collision zone. At the same time, previously deposited flysch sediments were incorporated into the accretionary wedge, further complicating the structural relationships. Obduction of the continental rise depositional sequence completely onto the shelf sequence

formed the present-day Taconic Allochthon (Figure 2E). At this time metamorphism of the rise sediments occurred, accompanied by the development of a slaty cleavage.

Austen Glen and related flysch (e.g., Utica, Schenectady) continued to be deposited to the west of the accretionary wedge. The climax of the Taconic Orogeny came when Grenville basement contacted the arc basement (Figure 2F). At this time basement faults, including some formed during the initial rifting of the Grenville supercontinent, were reactivated as reverse faults uplifting basement complexes such as the Berkshire, Housatonic, and Hudson Highlands massifs and transporting them to the west. The entire mass was then metamorphosed during the Taconic Orogeny, forming the Barrovian sequence we will see today. However, textural evidence of two episodes of deformation (folded cleavages, folded veins, and crenulation cleavages), are common in rocks of the Taconic Allochthon, the first fabric may have formed during obduction, the second during regional metamorphism.

Geochronology

Based on Rb-Sr and K-Ar studies, Long (1962) calculated a minimum age of 430 Ma for metamorphism during the Taconic Orogeny, followed by regional reheating at about 360 Ma. Taylor et al. (1999) used Lu-Hf systematics on garnet-whole rock pairs to date the metamorphism at around 440 Ma. The range of ages they calculated, along with data from both the core and rim of a garnet, suggested that prograde garnet growth occurred in only about 10 million years (446 Ma core, 436 Ma rim), implying a relatively short metamorphic event.

Metamorphism and P-T estimates

Metamorphic grade increases to the east-southeast across the county from practically unmetamorphosed shale at the Hudson River at Poughkeepsie, NY to high-grade gneiss at the Connecticut border east of Pawling, NY. The first appearances of the isograd minerals biotite, garnet, staurolite, kyanite, sillimanite, and orthoclase have been located (Barth, 1936; Vidale, 1974a; Whitney et al., 1996b). Sutter et al. (1985) have identified two different metamorphic events in Dutchess County. The first (their T-2 domain) was characterized by Barrovian metamorphism from chlorite to garnet grade along a gentle metamorphic gradient. The second (T-3 domain) was along a steeper metamorphic gradient resulting in closely spaced isograds from garnet to the first appearance of sillimanite-orthoclase. The data suggest that this higher grade event was a late structural event, and that the zone of maximum intensity of metamorphism corresponds to the area of maximum crustal thickening from imbricate thrusting late in the Taconian orogeny. Several inconsistencies in the simple story of prograde metamorphism, including the fact that fibrolitic

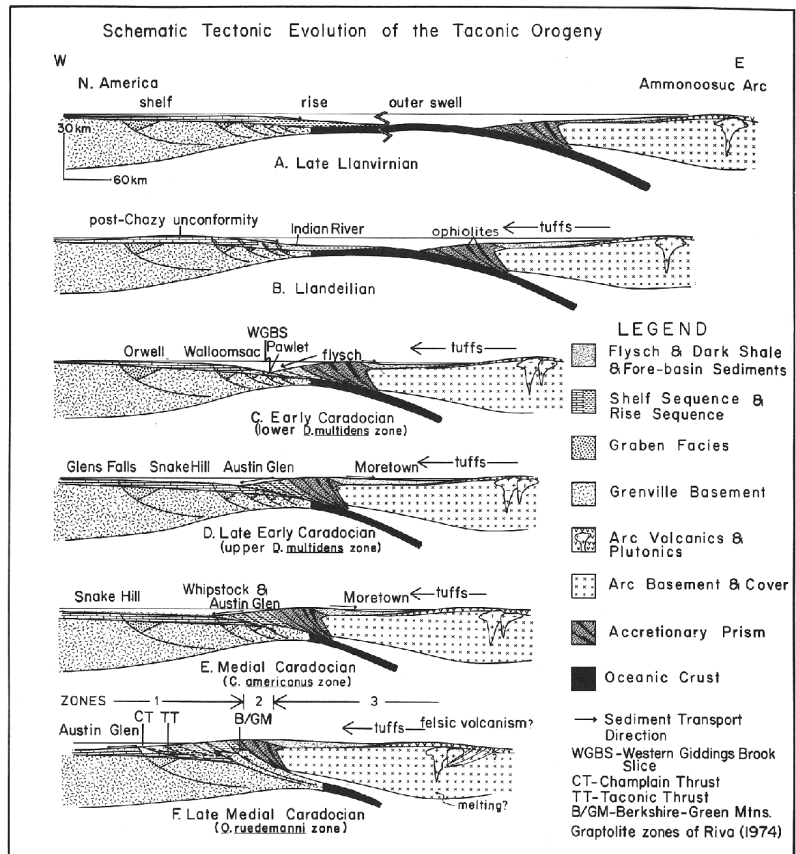


Figure 2. Sequential tectonic cross-sections for the Taconic Orogeny in New England. See text for discussion (from Rowley and Kidd, 1980).

sillimanite occurs at the same localities as the first appearance of kyanite (Figures 16 and 17), as well as the observation that garnets in the greenschist and amphibolite facies rocks (biotite, garnet and staurolite zones) appear to have been affected by circulating fluids (Whitney, 1996; Whitney et al., 1996a and b), may be related to this second, higher grade event. In addition, a range of protolith compositions, often in the same outcrop, demonstrate well the effects of bulk composition on mineral paragenesis.

Metamorphic grade increases to the east-southeast across the county from practically unmetamorphosed shale at the Hudson River at Poughkeepsie, NY to high-grade gneiss at the Connecticut border east of Pawling, NY. The first appearances of the isograd minerals biotite, garnet, staurolite, kyanite, sillimanite, and orthoclase have been located (Barth, 1936; Vidale, 1974a; Whitney et al., 1996b). Exceptions to this simple story of prograde metamorphism include the fact that fibrolitic sillimanite occurs at the same localities as the first appearance of kyanite (Stop 6), and the observation that garnets in the greenschist and amphibolite facies rocks (biotite, garnet and staurolite zones) appear to have been affected by circulating fluids (Whitney, 1996; Whitney et al., 1996a and b). In addition, a range of protolith compositions, often in the same outcrop, demonstrate well the effects of bulk composition on mineral paragenesis.

Where appropriate, each field trip stop description includes the possible mineral reactions as proposed by either Bence and McLelland (1976) or Whitney et al. (1996b). It is an interesting challenge to look for hand specimen evidence of the reactions; in some cases we have included thin section photomicrographs of reactions for which evidence is difficult to see in hand specimen.

Temperature estimates for the metamorphism of Dutchess County rocks have been made by a variety of techniques, and are relatively consistent. Oxygen isotope data (Garlick and Epstein, 1967) suggests a temperature range of 480-625°C for garnet through sillimanite zone metamorphism. Whitney et al. (1996b) used garnet-biotite geothermometry (Ferry and Spear, 1978) to calculate a temperature range of 435-590°C for the same zones, and added calculations from the sillimanite-orthoclase zone of around 730°C. Using the GPBM geobarometer (Ghent and Stout 1981) they also calculated a pressure range of 2-6 kbar for garnet through sillimanite-orthoclase rocks. Their results are plotted in Figure 3 (Whitney et al., 1996b) in which core and rim analyses from garnets at the same grade are plotted with the same symbols, illustrating possible P-T-t paths.

Veins and their relationship to matrix minerals

Quartz and calcite veins are common across Dutchess County. The calcite is presumably due to the dis-

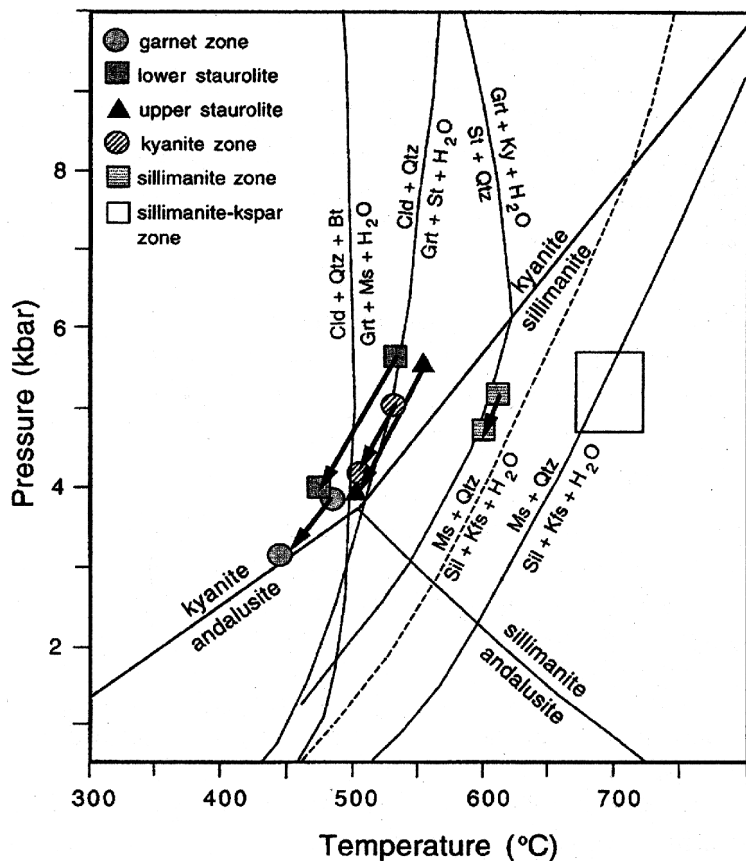


Figure 3. Petrogenetic grid for Dutchess County rocks (from Whitney et al., 1996b).

solution of the many carbonate rocks in the stratigraphic section. The quartz may be derived either from pressure solution during structural deformation, or from silica released to the system by metamorphic reactions especially at the lower grades. Thin sections clearly show evidence for pressure solution during slaty and crenulation cleavage formation. Veins exposed in outcrop are commonly folded, with a crenulation cleavage parallel to their axial surfaces (e.g, Stop 3).

Vidale (1974a) mapped veins throughout the county and found that their mineralogy correlated with increasing grade, with quartz and quartz-calcite veins below the staurolite isograd, quartz-plagioclase veins in the staurolite, kyanite and sillimanite zones, and quartz-plagioclase-orthoclase above the sillimanite-orthoclase isograd. Vidale (1974a) concluded that the different vein-types were related to increasing metamorphic grade, and that the material for the vein was derived from the surrounding matrix. It has since been proposed that some of the veins in the higher-grade rocks could be anatectic melts resulting from high temperatures and abundant aqueous fluids (Bence and McLelland, 1976).

Whitney et al. (1996a) proposed that the fluids which modified the metamorphic sequence migrated through the rocks both along fractures (to create veins) and along channels parallel to the foliation. These migrating fluids modified garnets at or near the peak metamorphic conditions (~525-550°C, ~4-5 kbar), just before the garnets stopped growing. Sr-isotopic studies of fluid inclusions in co-existing quartz and garnet (Whitney et al., 1999) indicate that the fluids in the minerals may have been different, suggesting that fluids trapped in garnets were not in equilibrium with matrix fluids trapped in quartz. In contrast, Whitney and Morrison (1997) determined that garnet and quartz oxygen isotopes were in equilibrium at least at higher grades. These studies indicate that fluid flow has significantly affected the rocks in this sequence and many complexities remain to be worked out.

Fabric development and metamorphic differentiation

Metamorphic fabrics at lower grades typically develop from the growth and rotation of platy minerals (phyllosilicates, graphite, hematite, ilmenite) perpendicular to the maximum shortening direction. The rocks here provide evidence that mass diffusive transfer (pressure solution) is an important mechanism for the development of cleavage domains particularly at lower grades. The classic progression of metamorphic rock fabric, from slate, to phyllite, shist and gneiss, closely correlates with increasing metamorphic grade across the Dutchess County. Crenulation cleavage is common, illustrating multiple deformation phases likely associated with allochthon emplacement (thin skin), later Taconic collisional-related shortening (basement involved), and probable Acadian overprint.

Index minerals, such as biotite, chloritoid, and staurolite have been observed to grow across fabrics, and kyanite appears to be randomly oriented within the foliation plans. This suggests that the metamorphic peak was probably reached after the main deformation phase ended. However, some porphyroblasts, especially garnet and chloritoid do show clear evidence of rotation relative to an earlier foliation (see Whitney et al., 1996; and examples at individual stops below).

Above the sillimanite isograd, schistosity begins to be replaced by gneissic layering, a fabric that then predominates in a zone sub-parallel to the NY-CT border. Vidale (1974b) concluded that this layering was a product of metamorphic differentiation possibly caused by the diffusion of components in response to local pressure gradients related to tectonic stress.

Structure and geologic cross section

The complex tectonic history of the Taconic Orogeny has resulted in a complex structural picture for Dutchess County. A schematic cross section approximately along the line of the field trip is shown in Figure 4. Formation names and symbols are taken from the Lower Hudson sheet of the NYS Geologic Map (Fisher et al., 1970) except as noted below. Important features of the cross section include: remnants of the Taconic klippe (labeled "Taconic sequence") which underlie topographic highs in the central part of the county; pC basement rocks and their Paleozoic cover raised along eastward-verging reverse or thrust faults (Ratcliffe and Burton, 1990); an overturned syncline involving the Wappinger Group carbonates and the Walloomsac formation in the eastern part of the section (McLelland and Fisher, 1976); and an interesting topographic inversion whereby carbonate rocks of the Wappinger Group are ridge-forming units in the western part of the county, and valley-forming units to the east.

Generalized Geologic Cross Section along NYS 55

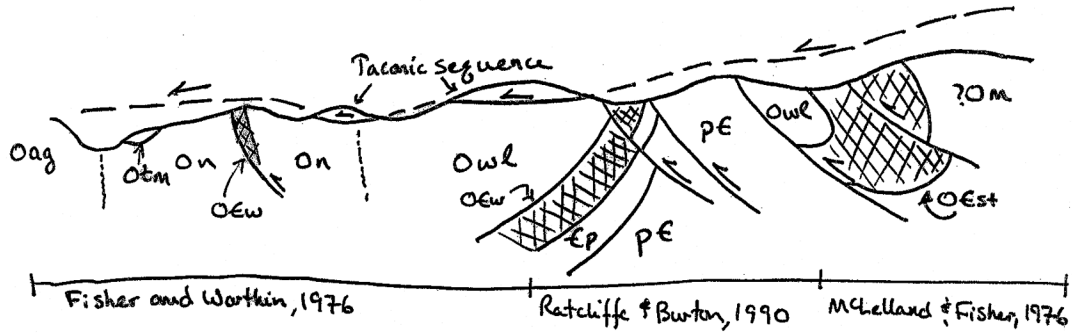


Figure 4. Generalized geologic cross section along NY Route 55 (adopted from Fisher and Warthin, 1976; Ratcliffe and Burton, 1990; and McLelland and Fisher, 1976).

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ROAD LOG

Miles	Route Description
0.0	0.0 Wooster Science Building (loading dock), SUNY New Paltz. Exit lot and turn left (north) onto NY 32 (S. Manheim Blvd.).
0.3	0.3 Turn right (east) at traffic light onto NY 299 (Main Street). Cross over NYS Thruway.
1.2	0.9 Traffic light at intersection with NYS Thruway entrance. Stay on NY 299.
6.8	5.6 Turn right (south) at traffic light onto US 9W.
8.7	1.9 Traffic light at Haviland Road. Continue straight, <i>or turn left for two optional stops.</i>
	(0.7) Small outcrop on left in Austin Glen Formation.

Optional Stop A - Austin Glen Formation (UTM 18T 0587118 4617922). Graywacke beds here show sedimentary structures indicative of deep marine turbidity deposits, including ripple marks, graded beds, and sole marks. Although these sedimentary structures show that the beds are upright, cleavage dips more gently than the upright bedding indicating downward facing structures (Figure 5). This illustrates the complex structural relationships found in this belt due to refolding and probable post-cleavage block rotation in front of the Taconic Allochthon.

(0.3) Continue to parking lot in Johnson Iorio Memorial Park.



Figure 5. Bedding-cleavage relationships in Austin Glen graywacke at Optional Stop A. Ripple marks, sole marks and graded beds (bottom right) demonstrate that these beds are upright. Cleavage (parallel to hammer handle) dips more gently than the bedding, indicating that the cleavage and associated folds are downward facing. Such complex relationships are common in this belt.



Figure 6. (right) Graywacke and shale of the Austin Glen Formation at Optional Stop B, Johnson Iorio Memorial Park. Thickest beds in photograph are approximately 20 cm.

Optional Stop B - Austin Glen Formation at Johnson Iorio Memorial Park (UTM 18T 0587209 4617483). Outcrops of Middle Ordovician Austin Glen Formation thick bedded graywacke and shale show sedimentary structures typical of these deep marine turbidity current deposits that were shed to the west off the rising Taconic Mountains (Figure 6). These deposits were subsequently deformed as the Taconic Allochthon overrode them from the east. Across the Hudson River can be seen outcrops of the Taconic melange, the main Taconic thrust zone (Stop 1), and the Taconic Range to the east. The rock in these cuts is particularly well exposed because of the high percentage of sandstone, more common shale rich exposures may be more representative of a protolith for metapelite outcrops visited at subsequent stops.

From optional stops, return to traffic light at Haviland Road and turn left (south) on US 9W.

- | | | |
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| 8.8 | 0.1 | Take ramp to right following signs for Mid-Hudson Bridge and US 44 - NY 55. |
| 9.5 | 0.7 | Toll booths for Mid-Hudson Bridge. |

Road cuts from here to the Mid-Hudson Bridge show excellent exposures of the Middle Ordovician Austin Glen Formation thick bedded graywacke and shale. The outcrop shows the variation in bed thickness and shale content, as well as numerous faults. See the descriptions above for similar exposures at Optional Stops A and B.

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| | | Cross the Mid-Hudson Bridge and keep to the left for the next intersection. |
| 11.2 | 1.7 | Turn left (north) at traffic light onto Jefferson Extension (aka S. Perry Street). |
| 11.2 | 1.7 | Turn left (west) at stop sign onto Union Street, which curves sharply to right (north) and becomes S. Clover Street. |
| 11.5 | 0.3 | Turn left (west) at traffic light on Main Street. Proceed under US 9, and over railroad bridge. |
| 11.7 | 0.2 | Turn left at traffic light onto Rinaldi Blvd. |
| 11.8 | 0.1 | Turn right onto Gerald Drive, following sign for Truck Route, proceeding through tunnel under Mid-Hudson Bridge. |
| 12.0 | 0.2 | Turn right onto Hendryk Drive into Kaal Park. |
| 12.1 | 0.1 | Park in lot at Kaal Park (City of Poughkeepsie Park). |

Stop 1 - Taconic Melange at Kaal Park (UTM 18T 0588112 4617257). Taconic melange at Kaal Park is the type locality of the Poughkeepsie Melange of Fisher. The Taconic melange is well exposed here, although large sections

are covered with poison ivy. The phacoidal, or scaly, cleavage is typical of melange fabric world-wide. The shale breaks into centimeter-scale lens-like phacoids whose surfaces are polished and striated. Blocks within the melange are mainly graywacke here, and probably represent a disrupted bedded sequence similar to exposures of Austin Glen on the west side of the river at Optional Stop A. Locally, however, limestone blocks occur within the melange suggesting a sedimentary olistostromal component. The Taconic melange is a thick (kilometer-scale) tectonostratigraphic unit that occurs along the western margin of the Taconic Allochthons in the northern Appalachians, and represents a complex syn-sedimentary fault zone associated with allochthon emplacement. To the north, the Taconic melange is unconformably overlain by the Silurian Helderberg Group (Vollmer, 1981), establishing its Taconian age.



Figure 7. Taconic melange at Stop 1, Kaal Park showing graywacke blocks in phacoidally cleaved shale matrix.

Many exposures of "Normanskill" or "Snake Hill" shale in the Poughkeepsie area show clasts suggestive of melange, and the Taconic melange is suggested to be a potential protolith for some of the metapelites (such as Walloomsac) examined at subsequent stops.

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| | | Retrace route to US 44 - NY 55, returning on Hendryk and Gerald Drives and Rinaldi Blvd. |
| 12.6 | 0.5 | Turn right (east) at traffic light from Rinaldi Blvd. onto Main Street. Turn right (south) at light onto N. Perry, and left (east) at traffic light on US 44 - NY 55. |
| 14.7 | 2.1 | Traffic light at Raymond Avenue (turn right for Vassar College). Continue straight on US 44 - NY 55. Pass outcrops of Taconic Melange before Raymond Avenue. |
| 14.9 | 0.2 | Bear right onto NY 55, leaving US 44. |
| 16.2 | 1.3 | Outcrop of Wappinger Group carbonates on right. <i>For optional stop C, park on Henmond Road to the right just past the outcrop and return on foot.</i> |

Optional Stop C - Wappinger Group Carbonates (UTM 18T 0593529 461 5609). Outcrop of Wappinger Group carbonates, possible protolith for metacarbonates to be examined at Stop 9.

- | | | |
|------|-----|---|
| 16.7 | 0.5 | Cross Wappinger Creek. |
| 17.1 | 0.4 | Bear right at traffic light onto DCR 21 (Noxon Road). |
| 19.8 | 2.7 | Cross DCR 49 (Titusville Road) at traffic light. |
| 22.2 | 2.4 | Cross Sprout Creek. |
| 22.4 | 0.2 | Pull off on left near large outcrops on both sides of road. |

Stop 2 - Chlorite Zone at Noxon Road (UTM 18T 0594925 4615132). These outcrops are within the Taconic Allochthon, and show considerable structural complexity. The rock here is chlorite grade, and exhibits slaty cleavage, abundant chevron folds, and crenulation cleavage that folds an earlier foliation subparallel to bedding. Thin sections show that cleavage formation is dominated by pressure solution, a likely source of quartz veins (Figure 8 and 9). Witney et al. (1996) suggest that the chlorite forms from clay minerals. These reactions release silica that may also contribute SiO₂ to the formation of quartz veins.

Four distinct lithologic units are present within these outcrops: graywacke and dark shale, green slates, red slates, and slate with interbedded micrite. The contacts do not trace directly across the road, and are either part of steeply plunging structures or are discontinuous. Fisher and Warthin (1976) and Bence and McLelland (1976) assign the graywacke unit to Mount Merino (at the far west end), and the other three to the Indian River Formation. Structur-

ally this outcrop lies within the Giddings Brook Slice, the the structurally lowest slice of the Taconic Allochthon (Stanley and Ratcliffe, 1985).

On the south side of the road, west of the main outcrops, are dark crenulated slates and folded graywacke beds. Bottom structures exposed in a meter-scale synform indicate the folds are upward facing. This unit is in contact with green slates further east on the north side of the outcrop, where quartz veining indicate faulting along the contact. It seems likely that this unit is equivalent to the Austin Glen/Pawlet, and represents flysh deposited on the continental rise and subsequently carried with the allochthon (see main text).

The bulk of the main outcrop consists of highly folded and crenulated green slate with some interbedded chert and siltstone, however on the south side of the road is a large section of red slates of typical Indian River aspect. Bence and McLelland (1976) report hematite is present in the red slates, and absent in the green slates. The presence of hematite in Indian River has been attributed to both primary and secondary origins (e.g., Bird and Dewey, 1970; Bence and McLelland, 1976), and may represent erosion of a weathered horizon exposed as a foreland bulge during the Taconic Orogeny. If the graywacke unit is Austin Glen/Pawlet, then the Mount Merino may be represented by the green slates with cherty interlayers.

At the eastern end of the outcrop on the north side, a unit of banded gray micrites and interlayered slate is in contact with the green slate. The contact between the two units is complex, and disruption of the micrite beds is suggestive of soft sediment deformation with a strong tectonic overprint. This unit is remarkably similar to thinly bedded brecciated micrites at Schodack Landing, also within the Giddings Brook slice, which have been interpreted as slump deposits on the continental slope (Bird and Dewey, 1975; Friedman, 1979). This unit likely has a similar origin.

As we drive east from this stop we will leave the Giddings Brook slice, and shortly enter the structurally higher Everett slice. The remaining metapelite stops, except possibly Stop 5, are below the Everett slice (Stanley and Ratcliffe, 1985).

Pull out WATCHING CAREFULLY FOR TRAFFIC and continue on DCR 21 (Noxon Road).

- 23.1 0.7 Turn left at intersection, following DCR 21 (Noxon Road).
- 23.3 0.2 Cross Jackson Creek
- 23.6 0.3 Cross underpass below Taconic Parkway.

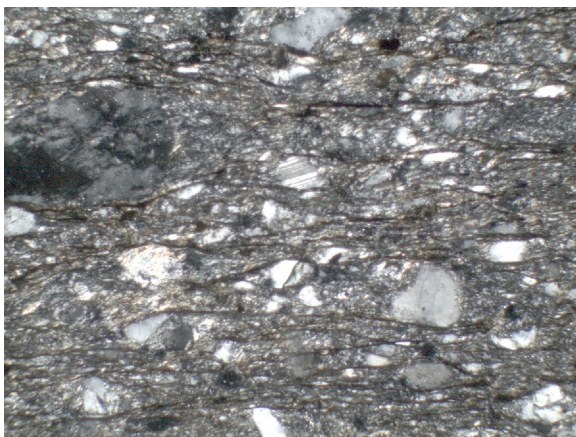


Figure 8. Thin section of graywacke (Austin Glen/Pawlet?) from Stop 2. Grains include abundant quartz, chert, lithic fragments, and feldspar (note plagioclase grain at center). A pressure solution cleavage (horizontal) truncates quartz grains. Field width 1.46 mm, CPL.

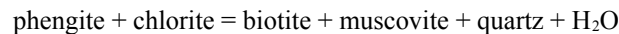


Figure 9. Thin section of kink fold and crenulation cleavage from Stop 2. The early foliation is bedding parallel and is folded by the later crenulation cleavage (vertical). The high phyllosilicate density in the crenulation cleavage domains suggests preferential dissolution of quartz. Field width 3.67 mm, PPL.

- 25.2 1.6 Cross DCR 82 at traffic light. Continue on DCR 21 (Noxon Road).
 26.8 1.6 Cross NY 55 at traffic light. Continue on DCR 21 (now Bruzgul Road).
 28.5 1.7 After following outcrops down hill on left, turn left on Perkins Lane (dirt) and pull off on right.

Stop 3 - Biotite Zone at Perkins Lane (18T 0608117 4612444). Black slates in biotite zone, although biotite is not visible in hand sample. These rocks are assigned to the Walloomsac Formation and are believed to be deposited on Wappinger Group shelf carbonates, which underlie Clove Valley just to the east. Thus, tectonically, these are exposed in a window and represent flysch overridden by the allochthon, or are brought up with basement by late reverse faults.

The main cleavage in the outcrop is relatively low angle, suggestive of high shear strains associated with allochthon emplacement. Numerous folded veins are related to shortening across the cleavage (Figure 10). Whitney, et al. (1996b) propose that biotite could form by the reaction:



An AFM projection for the upper biotite zone shows that at this grade biotite is stable for a wide range of pelitic compositions (Figure 11A).



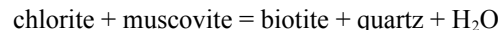
Figure 10. Folded veins with gently dipping axial planes parallel to crenulation cleavage at Stop 3.

- 28.8 0.3 *Lunch stop.* Turn right into Tymor Park (Town of Unionvale).

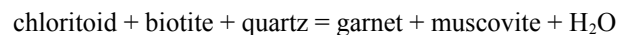
Lunch Stop - Tymor Park. South of the picnic area a dirt road runs through a spectacular gorge in the Wappingers Group dolostones to Furnace Pond. The pond was named either for a lime mill that stood on its shore (on Lime Mill Road), or for the Clove Springs Ironworks whose furnaces processed up to 700 tons of iron ore from Union Vale mines during the 19th century. Remains of the ironworks can be seen south of the park on Furnace Road.

- 29.7 0.9 Small traffic circle at intersection with DCR 9. Continue straight on DCR 21 (now Wingdale Mountain Road).
 30.4 0.7 Pull off on right, opposite gated dirt road.

Stop 4 - Garnet Zone at Wingdale Mountain Road (UTM 18T 0610910 4612446). Garnet zone with chloritoid. At this point we have crossed the garnet isograd, and garnets are now present in hand sample, although not always easy to find. Downhill from the parking area are biotite-bearing dark schists and metagraywackes (Figure 12). Garnet is found in the more fine-grained beds, which are presumably more aluminous than the graywackes. Whitney et al. (1996b) propose the reaction:



Across from the pull out, near a gated entrance, are chloritoid-bearing schists (Figures 13 and 14), suggesting the reaction:



Bence and McLelland (1976) attribute the mineralogical difference between these two outcrops to a more aluminous protolith, and the separation of the two bulk compositions by the garnet-chlorite tie line in an AKFM projection (Figure 11B). Note that the tie line switch in the biotite (Stop 3) to garnet (Stop 4) zone transition (Figures 11A and 11B) allows garnet to occur in typical pelitic compositions.

In thin sections from the lower outcrop, biotite is found growing across a crenulation cleavage, suggesting post-tectonic growth (Figure 12). Thin sections from the chloritoid-bearing outcrop show clear rotation of chloritoid and garnet porphyroblasts associated with shear strain (Figures 13 and 14). These porphyroblasts have overgrown an early foliation which has then been rotated during continued or later deformation.

Continue on DCR 21 (Wingdale Mountain Road).

32.9 2.5 *Alternate stop location with better parking than Stop 5 without requiring permission.* Pull out is on left at hair pin turn. It is suggested that cars turn around below and return to park on right, facing up hill. Outcrops are across from pull out and up hill on right.

Alternate Stop 5 - Stauroilite Zone (UTM 18T 0614569 4611725). See Whitney and Peck (2004) for a description of this outcrop.

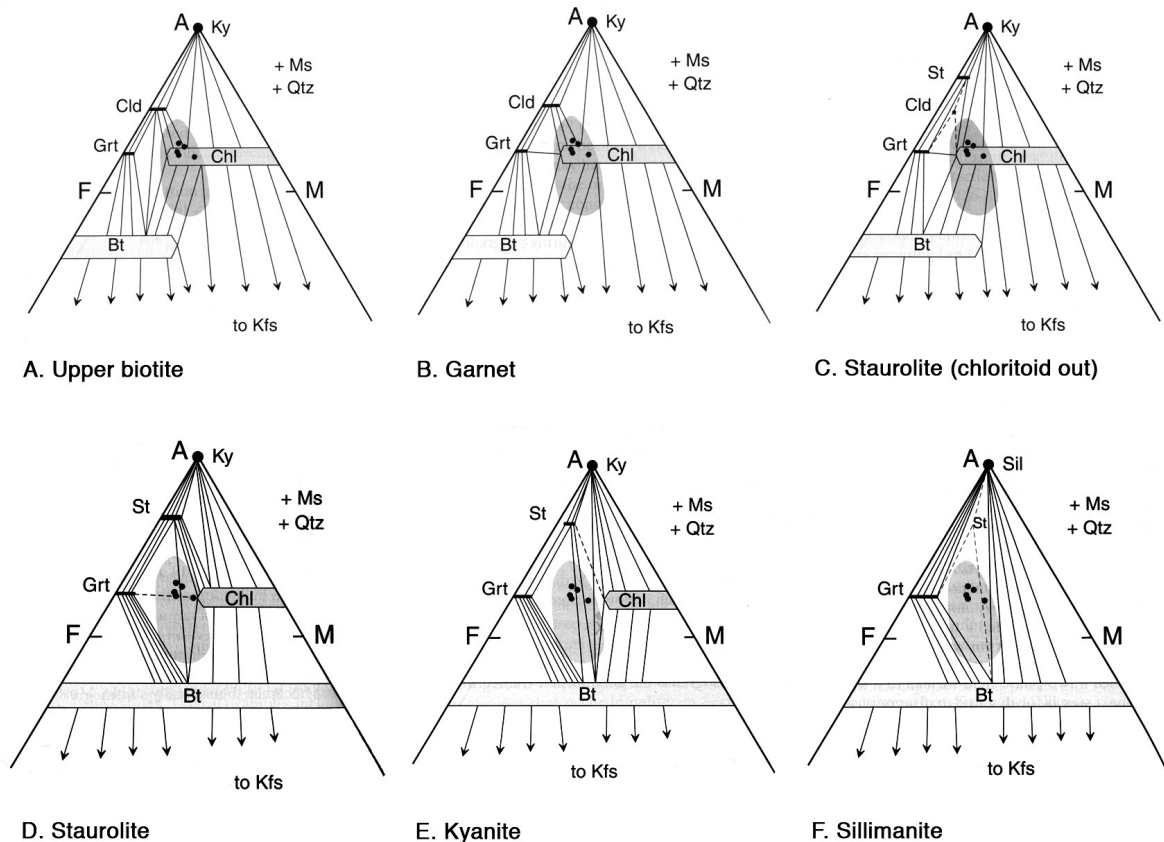
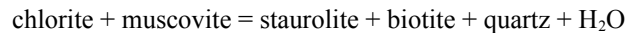


Figure 11. AKFM projections at several grades of metamorphism. The shaded area represents the composition of typical pelites (from Winter, 2001).

33.8 0.9 Pull off on right past Beebe Hill Road being VERY CAREFUL OF NARROW SHOULDER. Please do not park on Beebe Hill Road which is private and special permission must be obtained. You may wish to visit the alternate stop above for better parking.

Stop 5 - Staurolite Zone at Beebe Hill Road (UTM 18T 0615310 4611610). Coarse biotite-muscovite schists with garnet and staurolite porphyroblasts. Rocks here are now well within the staurolite zone, and contain centimeter scale garnet and staurolite porphyroblasts in the muscovite schist. This is the upper staurolite zone of Whitney, et al. (1996b), and because there is no chlorite in the rocks, the likely reaction is:



A tie line switch from garnet-chlorite to staurolite-biotite occurs at this grade, making staurolite stable over a wide range of pelitic compositions (Figure 11D).

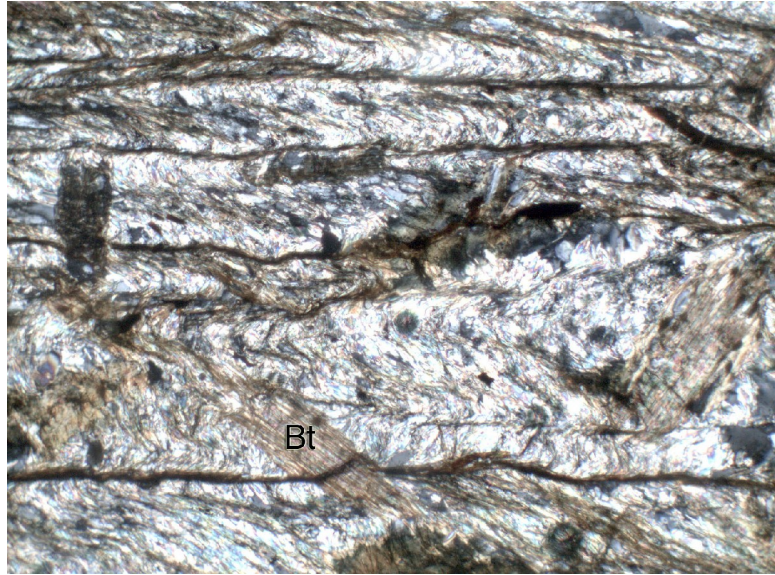


Figure 12. Thin section of non-chloritoid bearing schist from Stop 4 showing biotite overgrowing a crenulation cleavage. The earlier foliation (vertical) is folded by a crenulation cleavage (horizontal), and cross cut by the biotite, suggestion post-tectonic growth of the index mineral. Field width 1.46 mm, PPL.



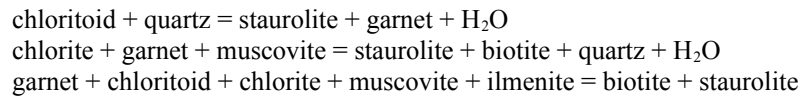
Figure 13. Thin section of chloritoid (center left) garnet schist from Stop 4. Top to right shear is shown by higher phyllosilicate density at top left and bottom right of garnet, and by bent ilmenite grains (opaque). Field width 3.67 mm, PPL.



Figure 14. Thin section showing rotated chloritoid in schist from Stop 4. Top to right shear is shown by: high phyllosilicate density at top left and bottom right, corresponding low density at top right and bottom left, rotation of an early overgrown foliation, and by bent ilmenite grain (top left). Field width 3.67 mm, CPL.

- Turn around CAREFULLY and return on DCR 21 (Wingdale Mountain Road).
- 35.4 1.6 Turn left on Pleasant Ridge Extension.
- 35.9 0.5 Turn left at stop sign onto Pleasant Ridge Road.
- 36.3 0.4 Intersection with Still Road. *Turn right onto Still Road for optional stop.*
- (0.7) Follow Still Road and turn around at Mennella Road.
- (0.1) Park on right across from small low outcrop of schists on left.

Optional Stop D - Lower Staurolite Zone at Still Road (UTM 18T 0611053 4611579). Please DO NOT HAMMER on outcrop. Chloritoid is partially replaced by staurolite, and prophyroblasts are difficult to see in hand sample. As noted by Bence and McLelland (1976), five coexisting ferromagnesian phases, garnet-chloritoid-staurolite-biotite-chlorite, can be identified in thin section, a disequilibrium assemblage violating the mineralogical phase rule (Figures 11C and 15). Three different reactions are possible here (Whitney et al., 1996b):



Careful study is needed to determine which reaction(s) are most likely because garnet may be either a product and a reactant. Figure 11C shows the chloritoid-out reaction, and the phase stability triangles for the five phases.

- (0.7) Turn right at stop sign back onto Pleasant Ridge Road.
- 39.5 3.2 Intersection of Pleasant Ridge Road and NY 55.

Optional Stop E - Poughquag Quartzite (UTM 18T 0610711 4606921). The Poughquag Quartzite is the basal unit overlying Precambrian gneisses here, and is correlative with the Potsdam sandstone and similar Cambrian basal units. On NY 55 to the left (east) the unconformity of the Poughquag Quartzite with underlying Precambrian gneisses is crossed proceeding uphill. These basement rocks were carried up on reverse faults, presumably later in the orogeny, and along steeper faults, when the continental basement eventually became involved in the collisional event.

- Turn left on NY 55.
- 40.9 1.4 Cross Appalachian Trail.
- 41.2 0.3 Pass intersection with Old Route 55 on left.
- 42.4 1.2 Pull over on right shoulder near large outcrops on both sides of the road.

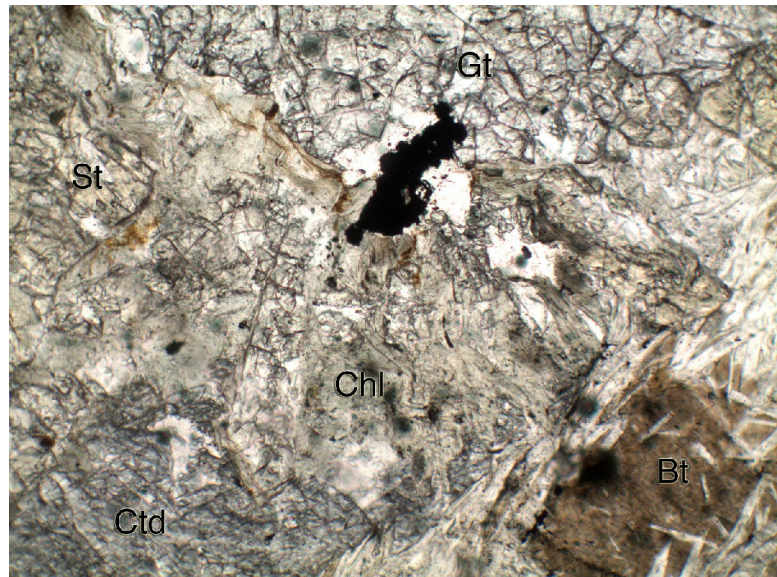
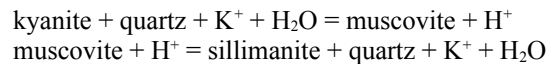


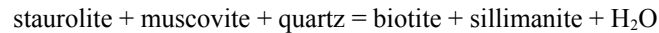
Figure 15. Thin section showing the five coexisting phases garnet-chloritoid-staurolite-biotite-chlorite at Optional Stop D. Coexistence of the five phases is an apparent violation of the phase rule (Figure 11C). Field width 1.46 mm, PPL.

Stop 6 - Kyanite Zone (UTM 18T 0613449 4603217). Kyanite is present as small 1-2 centimeter blue blades, but is difficult to find. It appears on weathered surfaces as white sprays or rosettes on foliation planes (Figure 16), apparently with no preferred linear alignment. **DO NOT HAMMER WEATHERED SURFACES**, samples may easily be obtained from fresh surfaces on existing road outcrops.

In thin section the assemblage kyanite-sillimanite-staurolite-garnet has been observed (Figures 17 and 18). The kyanite appears resorbed (Figure 17), and the presence of sillimanite as fibrolite (Figure 18) in the rocks suggests a captured divariant reaction, or disequilibrium (see Figures 3, 11E and 11F). Fibrolite has been observed in close proximity (millimeters) to the kyanite. One possibility is that linked reactions are occurring in adjacent local domains separated by a chemical potential gradient as proposed by Carmichael (see Blatt et al., 2006):



This allows the reaction to proceed without direct contact of the polymorphs. However, in the sample described here, this requires chemical potential gradients at a millimeter scale. Another possible reaction to explain the presence of fibrolite (Whitney et al., 1996b) is:



Again, this seems to require a strong chemical potential gradient and extremely limited fluid mobility.



Figure 16. Kyanite sprays in outcrop at Stop 6.

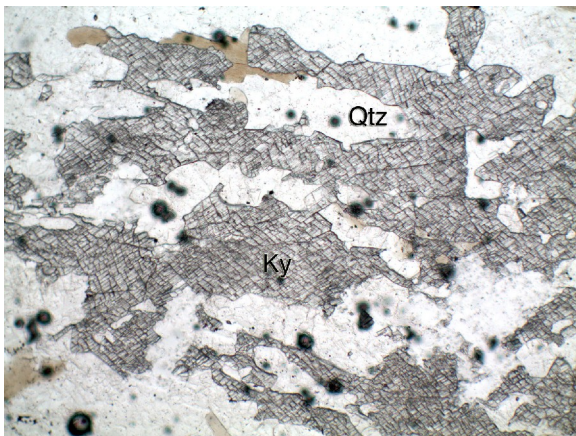


Figure 17. Thin section showing kyanite from Stop 6. In hand sample kyanite occurs as elongate needles, but shows irregular outlines in thin section suggesting it may be resorbed. Field width 1.46 mm, PPL.

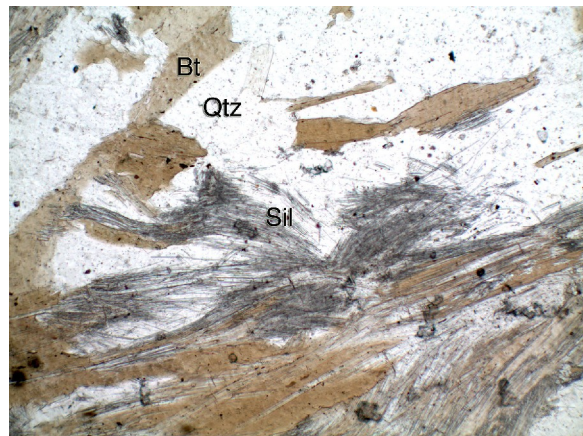


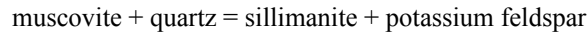
Figure 18. In the same thin section as Figure 17, within millimeters, is abundant sillimanite occurring as fibrolite. The occurrence of both implies a captured divariant reaction or disequilibrium. Field width 1.46 mm, PPL.

Whitney et al. (1996) noted that fibrolite first occurs in the kyanite zone. They discuss this in detail, and present several hypotheses to explain this. Variation in Mg content between layers and a reaction involving staurolite is ruled out by them, as they did not find evidence of staurolite in fibrolitic sillimanite-bearing layers. They suggest instead that the fibrolite may have grown at a later time (later Taconic or possibly Acadian), and that the reaction may be related to fluid infiltration, with fibrolite growth controlled by differences in local permeability and possible metasomatic Al-enrichment.

As discussed in the main text, two metamorphic events have been identified in Dutchess County (Sutter et al., 1985), and may be related to these perplexing apparent disequilibrium assemblages.

- | | | |
|------|-----|---|
| 45.1 | 2.7 | Pass outcrops of tremolite-diopside marble, which we will return to at Stop 9. |
| 46.1 | 1.0 | Cross over NY 22, taking ramp to follow NY 22 N. |
| 46.7 | 0.6 | Turn right at light onto Quaker Hill Road. |
| 49.3 | 2.6 | Park on right using CAUTION DUE TO NARROW SHOULDER. Hazard blinkers and flag person recommended. Alternate parking is just below hairpin curve at bottom of hill (UTM 18T 0619799 4602388). |

Stop 7 - Sillimanite Zone at Quaker Hill Road (UTM 18T 0620040 4602299). Prismatic sillimanite crystals are evident in thin section (Figure 19), but not visible in outcrop. Small pegmatite dikes containing tourmaline-muscovite-potassium feldspar-quartz intrude the sillimanite-garnet-muscovite schists, and provide evidence of anatectic melting (as opposed to quartz veins formed by lower temperature pressure solution dissolution and precipitation). In thin section (Figure 19) there is evidence for the reaction:



Note that the sillimanite between the muscovite and potassium feldspar has a coarser prismatic form than that between the quartz and potassium feldspar. A possible explanation is that ion mobility was greater along the muscovite-potassium feldspar interface than the quartz-potassium feldspar interface due to easier fluid migration, so growth was favored over nucleation.

- | | | |
|------|-----|---|
| | | Continue uphill on Quaker Hill Road. |
| 50.0 | 0.7 | Turn right at stop sign on DCR 66 (Old Quaker Hill Road). |
| 50.7 | 0.7 | Turn left on Burgess Road (dirt), park on right. |

Stop 8 - Sillimanite-Potassium Feldspar Zone at Burgess Road (UTM 18T 0621121 4600990). Manhattan schist here displays more pronounced gneissic banding, and tourmaline-muscovite-potassium feldspar-quartz pegmatite dikes. Whitney and Peck (2004) assign this outcrop to the Sillimanite-Potassium Feldspar zone.

- | | | |
|------|-----|---|
| | | Turn around and return on DCR 66 (Old Quaker Hill Road) |
| 51.6 | 0.9 | Turn left on Quaker Hill Road. |

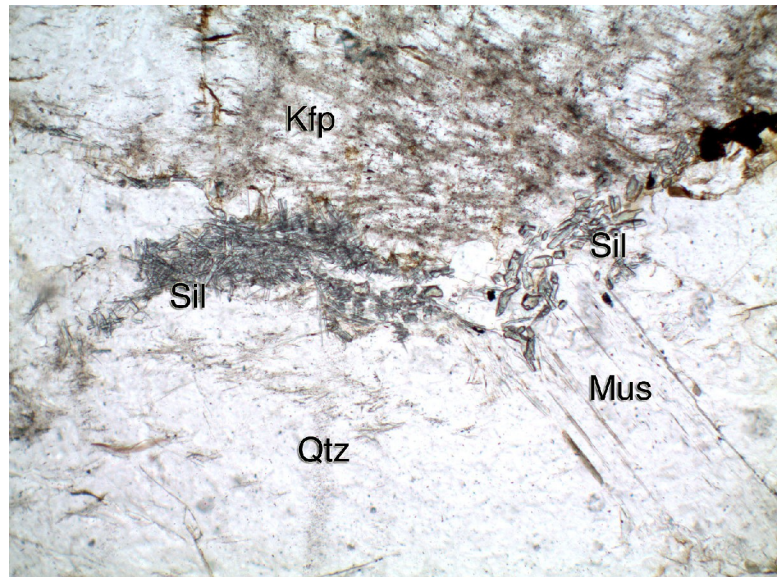


Figure 19. Thin section from Stop 7 showing prismatic sillimanite (as opposed to fibrolite) and reaction textures. Note that the sillimanite between the muscovite and potassium feldspar is a coarser prismatic form than that between the quartz and potassium feldspar. Field width 1.46 mm, PPL.



Figure 20. Diopside tablets at Stop 9.



Figure 21. Diopside sprays at Stop 9.

- | | | |
|------|-----|--|
| 54.8 | 3.2 | Turn left at traffic light on NY 22. |
| 54.9 | 0.1 | Bear right onto NY 55 toward Poughkeepsie. |
| 55.9 | 1.0 | Pull over on right shoulder near large outcrops. |

Stop 9 - Metacarbonates of the Briarcliff Dolostone (UTM 18T 0615950 4601071). Outcrops of diopside-trochilite-phlogopite marble that represent the metamorphism of carbonates to metamorphic grades approaching the sillimanite zone. One layer in particular contains a high concentration of diopside tablets and sprays (Figures 9 and 10). The diopsidic composition of these unusual forms was confirmed by thin section and X-ray diffraction analysis. Remnants of the less ductile silica-bearing beds within the marble record extreme ductile folding and boudinage, testifying to the high temperature deformation they enjoyed.

END OF FIELD TRIP. To return to New Paltz take NY 55 west, through Poughkeepsie to the Mid-Hudson Bridge. Once over the bridge follow US 9W north to NY 299. Take NY 299 west to New Paltz and NY 32 (or the NYS Thruway). Follow NY 32 south to the SUNY New Paltz Campus.

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